A Sensor Web Observing System Simulator

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Sensor Web observing systems may have the potential to significantly improve our ability to monitor, understand, and predict the evolution of rapidly evolving, transient, or variable environmental features and events. This improvement will come about by integrating novel data collection techniques, new improved instruments, emerging communications technologies, and interoperable planning and scheduling systems. In contrast with today's observing systems, "event-driven" sensor webs will synthesize near-real time measurements and information from other platforms and then reconfigure themselves to invoke new measurement modes and adaptive observation strategies. Meteorological prediction models may also serve to initiate new measurement modes (e.g., higher spatial, temporal resolution) or to target observations to specific regions. These "model-driven" sensor webs will complement event-driven measurements. Platforms will be tasked to target measurements within specific areas where sensitivity to initial conditions may cause ensemble forecasts to diverge when predicting the future state of atmospheric features (e.g., hurricane track) or when discriminating subtle yet critical differences in atmospheric states (e.g., winter precipitation type and location). The targeted measurements would then be assimilated to establish new initial conditions. This operations concept could contribute to reducing forecast model error growth, and concomitantly, forecast uncertainty. The sensor web concept contrasts with today's data collection techniques and observing system operations concepts. Although the technologies and capabilities of our space-, atmospheric-, and surface-based platforms and instruments have evolved significantly during the past four decades, operations concepts for present day observing systems remain essentially unchanged: independent platforms and instruments characterize today's "distributed data collection" systems. Information sharing between platforms and instruments, and interoperable planning and scheduling systems needed to coordinate and facilitate multiplatform measurements and sensor data fusion, are essentially non-existent. Sensor web observing systems, using closed loop controls between platforms and data assimilation and modeling processes, are expected to contribute to improving 10-14 day predictive weather forecast skill. However, investing in the design, implementation, and deployment of such a large, complex observing system would be very costly and almost certainly involve a great amount of risk. An analytical tool is needed to provide engineers and scientists with the ability to define, model, and objectively assess alternative sensor web system designs and to be able to quantitatively measure any improvement in predictive forecast skill. In this paper we describe a software architecture and the salient characteristics of a meteorological sensor web simulator. We believe the simulator could serve as a valuable tool to perform trade studies that: evaluate the impact of selecting different types and quantities of remote sensing and *in situ* sensors; characterize alternative platform vantage points and sensor measurement modes; and to test potential rules of interaction between components so that they collectively behave as a collaborative, dynamic environmental observing system. Candidate sensor web designs could be tested using well understood and documented past meteorological events or using current weather scenarios.

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I.   Introduction

Nearly half a century ago, on January 31, 1958, a 14kg, 95cm satellite, Explorer I, became the first successful US spacecraft placed on orbit. Its principal instrument, a cosmic ray detector, led to the discovery of the Van Allen radiation belts. Just over two years later, TIROS-1 became the first satellite to demonstrate the value of using polar orbiting satellites for global weather monitoring. By 1974, the SMS/GOES satellite series was complementing the TIROS satellites by providing continuous daytime and nighttime weather monitoring for an entire hemisphere from the unique vantage point of geosynchronous orbit. Today we take for granted the dozens of satellites and instruments that routinely and continuously monitor the Earth's land, oceans, and atmosphere returning terabytes of remotely sensed data daily. This space-based observing system, complemented by thousands of *in situ* measurement platforms and complex weather modeling systems, comprise a sophisticated global weather observing, data assimilation, and prediction system. The platform and instrument technologies and the number and types of measurements that are produced span a broad spectrum of capabilities: from surface-based *in situ* and remote sensing measurement systems to on-orbit remote sensing spacecraft with multispectral and hyperspectral imagers, microwave sounders, and radars. Measurement vantage points extend from the Earth's surface (e.g., Automated Surface Observing System, NEXRAD Doppler radars, moored and drifting buoys), through to the uppermost limits of the troposphere (e.g., radiosondes, dropsondes), and to low earth orbit (NOAA POES, NASA TRMM and Earth Observing System) and geosynchronous orbit (e.g., NOAA GOES series).

Yet, in at least one notable characteristic, today's observing systems do not significantly differ from their predecessors: platform and instrument measurements, and spacecraft mission operations concepts, are stovepiped. Although initial steps have recently been taken to foster integrated observing systems, with few exceptions measurement systems today are dominated by the use of independent platforms and science instruments. Information sharing among remote sensing platforms, and between remote sensing and *in situ* platforms, is typically not performed. Our space and ground segment infrastructure supports global, synoptic measurements, but it does not facilitate autonomous, collaborative data collection techniques or adaptive observing strategies. With few exceptions, instruments and platforms lack the ability to respond to rapidly evolving, transient, or variable conditions by reconfiguring spatial, temporal, or spectral measurement modes: instead, many operate in a single global data collection mode where the instrument is simply "on". Those platforms that are able to change instrument data collection modes primarily rely upon manual processes and procedures. Autonomous instrument reconfiguration is the rare exception rather than the norm: many constraints must be carefully considered and therefore instrument measurements are frequently planned and scheduled many days in advance. Disparate mission planning and scheduling systems, designed to meet specific mission measurement needs, are not interconnected. They lack the necessary middleware that could otherwise promote system interoperability and thus facilitate coordinated opportunistic, multisensor targeted measurements. Instead, measurements are reported on a nearly continuous basis guided by pre-established, somewhat rigorous data collection schedules. After performing instrument-unique data preprocessing, measurements are assimilated to create an updated set of initial conditions with which to initialize numerical weather prediction models. Forecast model runs are invoked at established, scheduled intervals throughout each day.

Today's global weather observing system has matured and evolved significantly during the past four decades: yet it can still be characterized as a large distributed data collection system composed of distinct, independent platforms and instruments. Data collection, communications, command, and control (C^3) are organized as a vertically structured system. It does not readily facilitate system elements to use horizontal sensor data fusion techniques and processes (i.e., information exchange and fusion across platforms, instruments, and C^3 systems). Observing system components are unable to access and utilize sensor measurement data and other useful information available from other platforms and predictive models that could potentially improve measurement decision making processes, increase instrument utilization efficiency, and maximize the return of the most useful science data. In contrast, sensor web observing systems would possess a certain form of situational awareness. By knowing, for example, that a global survey satellite sensor has detected clouds obscuring a primary target of interest, a pointable sensor on another spacecraft could instead change its measurement mode and point to a secondary, cloud free target. Similarly, if ensemble predictive models diverge due to measurement sensitivities in certain regions, that information could be used by the sensor web to autonomously deploy additional sensors (e.g., unmanned aerial vehicles - UAVs) to make targeted high resolution measurements within the region. These new, supplemental measurements would be assimilated to attempt to reduce model error growth. Subsequent sections summarize sensor web characteristics, provide our rationale for developing a sensor web simulator, and delineate its salient architectural features. The simulator thus offers significant potential to serve as a valuable tool with which to

perform trade studies that: evaluate the impact of selecting different types and quantities of remote sensing and *in situ* sensors; characterize alternative platform vantage points and sensor measurement modes; and to test potential rules of interaction between components so that they collectively behave as a collaborative, dynamic environmental observing system.

II. Sensor Web Overview

Although some of its intrinsic properties continue to be refined, we have characterized the sensor web as:

A sensor web is a coherent set of distributed nodes, interconnected by a communications fabric, that collectively behave as a single, dynamically adaptive, observing system.

The sensor web is composed of sensor, computing, and storage nodes.

Remote sensing and *in situ* sensors may be deployed on or below the Earth's surface (land, water), within the atmosphere, and in space. The platforms on which they reside may be stationary (e.g., moored ocean buoy, Doppler radar, a station-keeping high altitude balloon) or mobile (e.g., spacecraft, unmanned aerial vehicle, boat). Although not required, it is very desirable that sensors have more than one selectable measurement mode (e.g., low rate vs. high rate data collection; wide vs. narrow spatial field of view). Depending upon local processing bandwidth and storage capacities, sensor nodes will process their measurement data and may invoke specific algorithms commensurate with corresponding spatial, temporal, or spectral dynamics of the environment or event being monitored (e.g., marine pollution discrimination; harmful algal bloom detection). In addition to making measurements, sensor nodes interact with one another via the communications fabric. The communications

Node State Sequencing	Action
Event detection	▪ Discriminate and identify significant signals, features, patterns, …
Event notification	▪ Publish (subscribe to) event detection messages for potential use by other nodes
Event processing	▪ Exchange sensor data and other information ▪ Perform multi-sensor data fusion ▪ Refine event characterization
Node reaction	▪ Exchange node state messages to determine sensor and other available resources ▪ Modify science goals if necessary ▪ Plan new measurements ▪ Schedule new measurements

Table 1. Node State Sequencing

fabric enables sensor, computing, and storage node to exchange many forms of information such as raw or processed measurements, an instrument's measurement mode, a platform's state of health, and event detection notification messages. This information may be used to influence subsequent sensor measurements, change the initial conditions of a predictive forecast model, or to perhaps invoke a data mining algorithm to correlate new measurement data with retrospective information. The fabric may support a variety of communications mediums (e.g., wired or wireless; optical or radio frequency), protocols (e.g. terrestrial, space network), and topologies (e.g., tree, mesh). Subnet implementation may vary considerably depending upon application unique functional and performance requirements.

Sensor and computing nodes may perform multisensor data fusion using information derived

Node State Change	Examples
Spatial	▪ Move sensor to new location ▪ Change measurement resolution ▪ Increase/decrease field of view ▪ Point instrument to new target
Temporal	▪ Change sensor measurement frequency ▪ Invoke the next data assimilation or model run prior to scheduled run time
Spectral	▪ Select phenomena-specific sensor bands
Modeling and Data Assimilation	▪ Generate new set of initial conditions ▪ Invoke Mesoscale or nested grid model
Organizational	▪ Modify sensor network topology ▪ Form new sensor clusters ▪ Change cluster size ▪ Modify command and control hierarchy
Hardware and software	▪ Reconfigure sensor node FPGAs with different processing algorithm ▪ Execute event specific software

Table 2. Representative Node State Changes

from other complementary sensors. The exchange and synthesis of measurement data and other information (e.g., sensor location, sensor health, calibration or other ancillary information) in real- or near-real time can cause the sensor to autonomously react by changing to a new measurement mode or changing its information processing state (e.g., invoke a new algorithm; reconfigure a field programmable gate array - FPGA). Representative examples of node state sequencing and node state changes are listed in Tables 1 and 2. Information produced by one node can be transmitted to one or more other nodes using deterministic, triggered, or on-demand reporting methods.

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Deterministic reporting means that a sensor will make information (e.g., measurement data; event detection notifications; sensor health) available at predictable times. Triggered reporting occurs when a node detects one or more pre-established conditions that warrants information be immediately reported to one or more other nodes. On demand sensor reporting occurs when a node receives a request from one or more other nodes to immediately report requested information. Sensor reporting methods will impact the required communications fabric characteristics (e.g., media speed, network topology, communications protocols, network management, etc.).

A sensor web may consist of as few as two spacecraft flying in formation within the same orbital plane a few minutes apart. Alternatively, a sensor web may consist of a self-navigating littoral fleet that autonomously makes *in situ* measurements to detect and map pollutants in an estuary or bay. A sensor web that utilizes remote sensing and *in situ* sensors located in space, within the atmosphere, and on or below the Earth's surface would clearly have the advantage of making measurements over a very large spatial extent, possess the potential for frequent observations, and would be able to leverage the synthesis of complementary sensor measurements. What distinguishes the sensor web from today's distributed data collection systems is the *behavior* of the system: the ability of the sensors to perform as a coordinated, collaborative team. It uses the communications fabric to exchange measurement data and other information, and then dynamically reconfigures measurement modes to improve the observing strategy, in ways that tend to maximize the return of only the most useful information to scientists, policy makers, and decision support systems (e.g., emergency management). The feedback loop that serves to continually modify sensor measurement and information processing states is the critical new component that is expected to yield a substantial improvement in our ability to better understand the dynamic interrelationships that drive the formation, behavior, and evolution of a wide variety of environmental phenomena. The potential benefits of this new closed-loop approach are especially noteworthy. Using this teamwork like approach, coupled with autonomous decision making, it is envisioned that sensor web observing systems will: (i) maximize the return of only the most useful scientific measurement data; (ii) minimize observing system response time when monitoring rapidly evolving, variable, or transient phenomena; and (iii) perform targeted measurements within model-sensitive regions so that the new measurements can be assimilated to constrain model error growth and thus improve predictive forecast skill.

Computing and storage nodes complement the sensor nodes. A data assimilation and predictive weather forecast model is an example of a computing node. Storage nodes may provide other sensor nodes with processed measurement data. Intelligent archive storage nodes may mine meteorological repositories and provide derived information, such as historical trends, that can be used to refine where sensor nodes should make targeted observations in anticipation of the formation of a significant atmospheric state.

The sensor web architecture must permit nodes to aggregate over time, be replaced, upgraded with new hardware or software, and it must accommodate automated rerouting of information from failed or degraded nodes. The architecture must also be scalable to ensure that any significant changes (e.g., a large increase in the number of sensor nodes) will not significantly reduce overall system throughput and response time. This is significant because it is envisioned that the sensor web concept will play an important role supporting near real time decision support systems. As with large networked computers, a sensor web architecture must accommodate different sensor web topologies and node relationships (e.g., hierarchical vs. fully connected mesh; node clusters), different command and control mechanisms (e.g., centralized vs. peer-to-peer), and permit two or more sensor webs to logically combine to temporarily form a new, larger sensor web observing system. After the required observations are performed, the system may then re-form into the two independent, smaller subnets. The ability of the sensor web to successfully communicate and exchange measurement data and other information (e.g., event notification messages) will rely upon an underlying suite of technologies to seamlessly exchange information between nodes. Data and metadata representation standards will therefore be critical elements to ensure all data and information can be exchanged with syntactic and semantic ease.

III.   Sensor Web Simulator Rationale

The idea of a future global, interactive, sensor web observing system that is able to autonomously perform targeted measurements driven by events detected by other platforms and instruments, or driven by atmospheric data assimilation systems and weather models to constrain forecast model error growth and improve predictive skill is very compelling. Yet such a belief is insufficient: candidate designs for the concept must be developed and then objectively evaluated. Investing in the design, implementation, and deployment of such a large, complex observing system would be very costly and almost certainly involve a great amount of risk. The sensor web simulator is an analytical tool that can provide engineers and scientists with the ability to define, model, and objectively assess alternative sensor web system designs to quantitatively measure any anticipated improvement in predictive forecast skill. Such a tool can be realized by leveraging extensive experience in the development and application of

Observing System Simulation Experiment (OSSE) software at Goddard, and by integrating off-the-shelf simulation software with custom developed applications software. The simulator will be of significant value to evaluate the potential performance of candidate sensor web observing system designs. We hope to be able to objectively answer questions such as: What measurable improvement to the forecast process might be realized if the number and types of observing system platforms remain the same, but the rules of interaction between sensors and the modeling/data assimilation systems are modified to facilitate dynamic reconfiguration and targeted measurements?"

IV. Sensor Web Simulator Software Architecture

The Sensor Web Simulator (SWS) is based on the concepts described in "Advanced Weather Prediction Technologies Two way Interactive Sensor Web & Modeling System: Phase II Vision Architecture Study", November 1, 2003[1]. The system described in that weather architecture study consists of five main elements: (i) a Collection System; (ii) a Modeling and Data Assimilation System; (iii) Forecast Operations; (iv) an External Control System; and (v) a Communications, Command and Control System. The simulator will emulate the functions provided by the five elements described in the study.

The Sensor Web Simulator will provide an interface to administer the system by configuring new instrument types, platforms, and targeting schemes. An administrator may develop a new instrument or add new nature run data (i.e., a simulated representation of the real world), run simulation tests to validate realistic operation and evaluate the results. A simulation experiment can include a significant number of platforms and instruments. The majority of these will probably not change from one experiment to the next and it is expected that the simulation operator will want to select sets of these assets to be used for experiments. The SWS will allow creating a new a base collection of platforms and instruments and storing them in a repository that can be used in future simulator configurations. Existing base collections from the repository can be modified to fit new experiments. The simulation will allow an operator to set up a base configuration for the simulation trial based on the test scenario. The operator can alter the base configuration according to the scenario test parameters and execute the simulation trial using the new configuration

The sensor web simulation can be operated in two modes: a graphical, interactive interface for a user who wants to fine-tune the simulation as it progresses, and command-line batch processing where the user will only run the simulation to completion. In an interactive mode, the operator can control the execution of the simulation and monitor its progress. The simulator will provide the user with graphic displays showing asset locations, flight paths and ground tracks, current weather conditions, etc. An operator will be able to interact with the simulation and can make adjustments to the assets, priorities and analysis products from the sensitivity and weather analysis systems.

An analyst can review simulation output data and compare it with other simulation experiments. A simulation analyst can collect the simulation results for each particular simulation run. Each simulation run will have variations that can be compared in order to evaluate the specific feature under investigation. The simulator will provide tools for comparison and analysis. Upon analysis completion a report can be generated to recommend further experiments or document final conclusions. The Simulator:

- Allows the creation of a set of instruments/platforms for specific simulation experiments
- Controls the movement and operation of defined instrument/platforms.
- Controls the collection and distribution of observation data by the defined instruments
- Provides the capability to perform data assimilation
- Provides the capability to generate forecasts from the model.
- Provides the capability to analyze the forecast results and provide feedback to the system
- Provides the capability to analyze the results of the each experiment.
- Provides the capability for the user to interactively control the experiment

Figure 1 (next page) illustrates the major functional modules that comprise the simulator's architectural design. A description of the architecture's major modules, and significant subordinate functions, are delineated in Table 3 (next page).
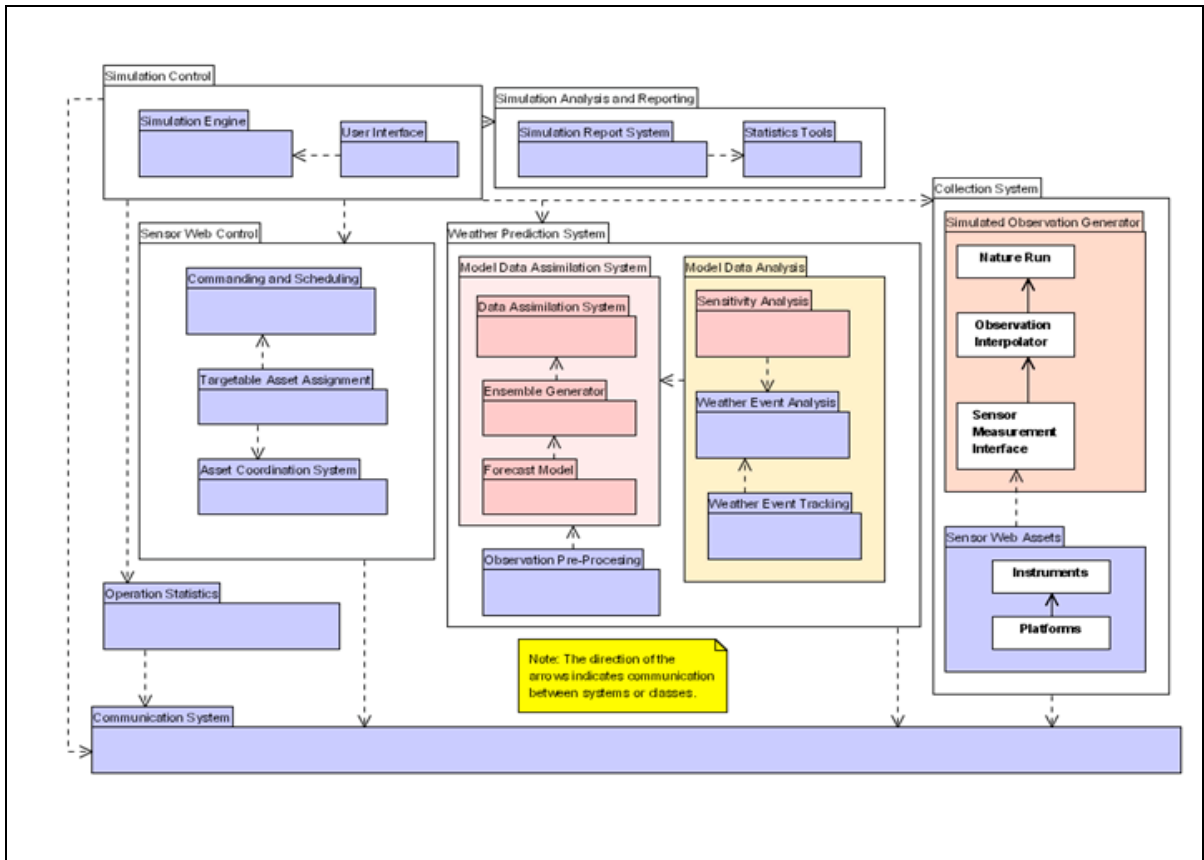
Figure 1 - Modular Decomposition of the SWS

Component	Description
Collection System	Gathers information about the environment. For the simulator, this includes the Simulated Observation Generator, Sensor Web Assets and Observation Pre-processing.
Simulated Observation Generator	*Provides a simulated representation of the real world (i.e. a "Nature Run") and the methods necessary to convert that representation into instrument observations consistent with the defined instrument/platform characteristics and the values contained in the nature run.*
Nature Run	A simulated representation of the state of the environment. The nature run data is created using a state of the art weather forecast model at high resolution. The weather forecast model is given an initial state consistent with real world observations. The model is then initiated and generates a free forecast at a set interval (currently 6 hours) from the beginning of the nature run period until the end of the period. The resulting data sets produced by the weather forecast model comprise the nature run. The data sets are validated so that they can be used as the reference, real-world atmosphere. The simulated atmosphere produced by this nature run can then be "sampled" by the SWS platforms to generate simulated observations. The generation of the nature run is not the direct responsibility of the SWS; however, a nature run might be initiated by collaborators to achieve some study goal of interest to the SWS users.
Observation Interpolator	Accepts nature run data as an input and interpolates it in both time and space to provide corresponding values for simulated observations at the locations and times specified by the instrument observation request. It does not apply any corrections based on instrument characteristics.
Sensor Measurement Interface	Adjusts the time and space interpolated nature run values provided by the observation interpolator to create a measured value that is consistent with specific instrument characteristics. It provides methods that account for measurement errors, platform or instrument look angles and spatial resolution filtering for specific instrument types to create simulated observations that are consistent with the instruments characteristics.

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Component	Description
Sensor Web Assets	A set of objects that are used to instantiate a specific sensor web experiment. Assets may include instruments and platforms, bases and command stations, and communication links.
Observation Pre-Processing	Provides the capability to apply filters, error corrections and other preconditioning functions to selected sets of the simulated observations prior to starting the assimilation process. In particular, it enables the application of statistical errors that require a complete set of observations and cannot be applied during the calculation of individual measurements by an instrument.
Sensor Web Control	*Directs the operation of the sensor web assets*
	Commanding and Scheduling — Manages sensor web assets by setting their basic collection and movement schedules. Assets are allocated based on collection priorities. Provides schedule information on available assets.
	Targetable Asset Assignment — Analyzes sensitive regions and weather events identified by the forecast analysis system and identifies the most appropriate mobile collection assets required to target them. Uses sensitive regions, event tracking information and other information (e.g. populated areas, shipping lanes) to determine priorities for assigning targetable collection assets. Requests a list of available assets that are within range of sensitive regions or weather events, identifies the most appropriate ones, and sends updated schedule requests to the scheduling system for assets to target the specified areas.
	Asset Coordination System — Guides the usage of sensor web assets. It establishes guidelines that affect how and when the assets can be controlled or the data derived from it can be accessed. This reflects various international and organizational protocols and priorities.
Weather Prediction System	Provides the functionality necessary to merge new observations collected by the SWS into its forecast model and analysis. It will generate ensembles of model forecasts and analyze, identify and track: weather events; determine forecast sensitivity to initial conditions and the geographic areas of sensitivity; and times and types of observations required to improve forecasts.
Model Data Assimilation System	*Analyzes the observation data and generates forecasts*
	Data Assimilation System — A numerical algorithm that integrates new observational data into a model state supplied by a prior forecast, defining an "assimilation model state" that is used as the initial conditions for a new weather forecast.
	Ensemble Generator — Takes the assimilation model state and produces a set of "ensemble model states" that are used to create ensemble forecasts for doing sensitivity analysis and weather event analysis and tracking.
	Forecast Model — Takes initial conditions from a model state produced by the ensemble generator and produces a free forecast.
Model Data Analysis	*Analyzes the forecasts results and generates event tracking and targeting information*
	Sensitivity Analysis System — Uses the forecast model output and information relating to weather event locations to produce sensitive regions that can be used to target areas for further observation.
	Weather Event Analysis — Uses the assimilation model state and free forecasts to identify important current or future weather events and provides an estimate of their probability, potential severity, and impact. A list of weather event locations is provided to the sensitivity analysis and weather event tracking components for further processing.
	Weather Event Tracking — Analyzes the assimilation model state and ensemble forecasts to determine the most likely paths of weather events identified by the weather event analysis component.
Simulation Control & Status	*Provides the ability to configure, control and monitor the execution of the simulator. It allows the user to interact with the system and determines the flow of control between the each of the system's components*
	Simulation Engine — A graphical interface that allows the user to display controls, plots and graphs, and system status.
	User Interface — Drives the simulation process. It provides the control loop that notifies parts of the simulator when to update platform locations, start pre-processing observations, assimilate observations, analyze model sensitivity, apply targeting algorithms, update schedules, and update user displays. It determines when to write restart files, and logs files.
Operation Statistics	Collects information about the execution of a simulation experiment. It allows the user to look at observation collection and distributions, effectiveness of automatic targeting and asset commanding.
Simulation Analysis & Reporting	*Aids simulation experiment analysis by collecting information, generating statistics and creating reports*
	Statistics Tools — Provide functions that generate various statistics on the simulation output.
	Simulation Report System — Uses Statistics Tools to generate reports (e.g., system metrics, forecast improvements) based on the simulation run. Can be used to quantify the value of a particular simulation.

Table 3 – SWS Functional Components Summary

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The sensor web simulator requires a significant amount of complex functionality to implement a complete simulation. However, there are existing software and COTS products that can be adapted to meet the simulator's requirements. The OSSE work performed at NASA's Goddard Space Flight Center provides a solid foundation for building the simulated observation generator portion of the simulator. The Earth System Modeling Framework (ESMF) can provide common interface and data exchange mechanisms that simplify integration of data assimilation and weather forecast models into the SWS system. Additionally, Analytical Graphics, Inc. product, Satellite Tool Kit (STK) with its Connect interface and Advanced Visualization Option (AVO) is well suited to managing position and movement of collection assets as well as providing a visualization and analysis interface for the system user.

V. Representative Sensor Web Simulator Case Study

A. Background

In the process of evolving the design of a new system it is often useful to validate it with relevant use cases. This was the approach taken in the second of two Earth Science Technology Office (ESTO) studies[1] that proposed using sensor web concepts as a critical part of a future operational weather forecasting system. The first study[2] examined technology that could improve weather forecasting dramatically by the year 2025. The second study focused on an intermediate time period (2015) and observing systems assets already in the pipeline for that time period. In both cases, the presence of a strong feedback loop between the modeling and assimilation system and the observing system was assumed, allowing the system to adjust its operations in an optimum way to improve weather forecasts.

The use case for the second study[1] was the US East coast Blizzard of 2000. In the sections below we will describe how the SWS simulator could be configured to address that use case. We first describe the Blizzard of 2000 and the operational forecast issues. Next the 2015 Observing System is described. Then, the capabilities needed to model the 2015 Weather Forecast System in the SWS are described. Finally, an example of how the SWS would be used to model targeted observing for the Blizzard of 2000 use case is described.

B. The US East Coast Blizzard of 2000

The Blizzard of 2000 occurred on January 24 and 25, 2000. It was selected as a use case for the ESTO study because it had been widely documented in the literature [3,4,5,6,7], had large economic impacts over a wide geographic area, and was recognized as a major failure of the operational forecast systems at the time. The storm system had its origins in the middle Pacific Ocean as an upper level disturbance, began developing as a surface low pressure feature in the Gulf of Mexico, and rapidly intensified off the US east coast. The storm resulted in a large area of unpredicted heavy snow from the Carolinas, through the mid-Atlantic coast, into the northeast.

Numerical weather prediction (NWP) forecasts for the Blizzard of 2000 had problems in both the medium range and the short range. In the medium-range (3-5 days prior to the event), the storm was predicted to be well off of the east coast and weak; not impacting populated areas. In the short range (24 to 48 hours prior to the event), the forecasts continued to show weak development and a track further east than the actual path of the storm.

The accuracy of NWP forecasts is dependent on many factors, including spatial and temporal resolution of the model, model physics, etc. Another major factor affecting the accuracy of forecasts is the quality of the initial atmospheric conditions specified to the model. The initial conditions provide a three dimensional description of the atmospheric state over the entire domain of interest. Parameters such as temperature, moisture, and winds are specified at each grid point of the model domain. These parameters are determined by optimally combining observations with previous forecast data in a process called data assimilation.

The Blizzard of 2000 had its origins in the mid-Pacific Ocean. This area has poor data coverage, relative to the mainland US, particularly for wind data. Over the US mainland, wind profile data (as well as temperature and moisture profiles) are provided every 12 hours via the rawinsonde network. Over oceanic areas, no such network exists, although temperature and moisture profile data are provide by satellite-based sounders. As a result, the specified initial conditions for a storm system originating in the mid-Pacific can be problematic, as was the case with this storm system.

C. The 2015 Observing System

Observing System components assumed for 2015 contain planned operational systems including NPOESS, GPM, GOES-R, surface observation network (including mesonets), rawinsonde network, radar data, sounder data and the aerial collection of upper air data via dropsondes. In addition, it is assumed the weather data measurements from commercial aircraft are available to the system. Satellite local refresh of polar orbiters are assumed to occur

approximately every three hours; geostationary data from GOES-R collected every 5 minutes with the ability to focus collections in mesoscale regions at higher spatial and temporal resolution. The satellite observations will provide imagery and infrared and microwave sounder data. The latter will provide temperature and moisture profile data that are most accurate over regions with limited cloud cover. Even in 2015, it is assumed that the primary source for vertical profiles of wind data will be from the rawinsonde and sounder networks over land areas (there will be some shipboard information). In cases where accurate wind profiles are needed for targeted observing over data sparse (e.g., oceanic) regions, aircraft measurements and dropsonde data will generally be required. A further assumption of the 2015 observing system is that the routine surface (hourly) and rawinsonde (every 12 hours) observation schedule can be modified to accommodate operational requirements for more data.

D. Using the SWS to Apply the 2015 Weather Forecasting System against the Blizzard of 2000 scenario
In order to apply the SWS to the Blizzard of 2000 scenario using the 2015 Weather Forecasting System a number of steps need to be accomplished:
- The SWS needs to be configured to match 2015 Observing system capabilities
- The 2015 Sensor Web Control, Weather Prediction, and Collection systems needs to be specified, consistent with the capabilities of the 2015 Weather Forecasting System
- A suitable nature run that captures the Blizzard of 2000 scenario must be generated and used

As mentioned above, the 2015 Observing assets are assumed to include NPOESS, GOES-R, the surface observation network, the rawinsonde network, and aircraft measurements for targeted observing. For the satellite-based portions of the observing system (NPOESS and GOES-R), orbital characteristics and data measurement patterns would need to be defined. In addition, the measurement characteristics (e.g., spatial resolution, accuracy, and precision) of meteorological parameters (e.g., temperature, moisture, clouds, etc.) would need to be specified based upon system requirements and specifications. The 2015 surface observation and rawinsonde network would probably be similar to today's networks, but again the measurement characteristics of these systems would need to be specified in the simulator. Finally, aircraft assets would need to be defined, whose flight patterns are configurable and whose measurement capabilities specified. The schedule and characteristics of the observing system assets would be used by the SWS Simulated Observation Generator to provide simulated measurements for all assets for the entire simulation.
We assume some flexibility in the collection schedules of the above assets:
- One or more GOES-R mesoscale regions can be set up anywhere and at any time within the GOES collection field-of-view
- The collection schedule of surface observation and rawinsonde network can be modified
- Aircraft assets with meteorological collection capability can be allocated and assigned to missions to collect meteorological observations.

The 2015 system would include several other components:
- One or more medium range NWP models and assimilation systems (e.g., next generation WRF, NASA GEOS-5, etc.).
- Models to perform sensitivity analysis to determine where forecasts are most sensitive (sensitivity analysis of adjoints and/or ensembles, etc)
- Functionality to identify and track meteorological features of interest
- Functionality to assign the 2015 Observing System assets to collect data in regions that will most improve forecast accuracy.

Of these, the modeling capability currently exists for the first two bulleted items, but would ultimately need to be developed for the latter two. Once these capabilities are in place, the SWS could be used to study the impact of targeted observing using 2015 assets on the medium range forecast for the Blizzard of 2000.

E. Application
In this section we show how the SWS would apply targeted observations during the medium range forecast stage of the Blizzard of 2000, approximately three days prior to the blizzard. We assume that by 3-days in advance of the storm the SWS Weather Prediction System has identified the "potential" of an east coast storm. At this point, the Weather Prediction System is tasked to perform a sensitivity analysis to determine where, what, and when observations should be collected in order to improve forecasts. The Sensor Web Control function then uses the sensitivity analysis to identify and assign assets to collect the required data. The goal is to maximize the spatial and temporal overlap of measurements from multiple sensors, in order to obtain as complete a picture of the atmospheric

state as possible within narrow time windows. Using 2015 assets, this means that the Sensor Web Control function seeks to schedule coincident collections from satellite (e.g., NPOESS, GOES-R, etc.), in-situ (e.g., rawinsondes, dropsondes, aircraft) and ground-based (e.g., surface observations, profilers) platforms. Advantages of coincident collections include:

- Accurate first guess profiles from rawinsondes and dropsondes for NPOESS, GOES-R, and other retrieval algorithms. This effectively spreads the quality of the in-situ measurements to the denser, but sometimes less accurate satellite measurements. This procedure improves the quality of satellite retrievals, especially in regions of extensive cloud cover.
- Widespread, high-quality measurements for data assimilation to improve the definition of the initial state of the atmosphere.

Based on the sensitivity analysis and the observing system schedule, the Sensor Web Control directs intermediate launch of rawinsondes over land areas in the region of highest sensitivity. The Sensor Web Control also directs aircraft collections. The sensitivity analysis shows that more accurate measurements of wind speed, temperature, and the height of standard and significant pressure levels are needed off the US West Coast where rawinsonde measurements are not possible. The Sensor Web Control directs the flight pattern and timing for aircraft measurements using dropsondes to "sound" the atmosphere.

Although rawinsondes and dropsondes provide the most accurate measurements of temperature, moisture, and wind data, their geographical distribution is limited relative to the coverage of meteorological satellites. In an effort to capture a more complete picture of the atmospheric state in the sensitive regions, the Sensor Web Control schedules GOES-R mesoscale regions to be set up over two zones to cover the aircraft (ocean) and rawinsonde (land) measurement areas. Both imagery and sounding products will be collected over these regions. In addition, the Sensor Web Control schedules the rawinsonde and aircraft collections to be at approximately the same time as the NPOESS-PM satellite overpass, so that the in-situ measurements can best support the NPOESS retrieval algorithms.

The above allocation of observational resources is intended to collect data to improve the initial conditions for the next data assimilation and forecast cycle, which is scheduled by the Weather Prediction System to occur subsequent to the collection of the above data. Improved initial conditions due to targeted observing should lead to better forecasts. But how might this be evaluated? One way would be to establish a *control* Weather Forecast system that is not allowed to adjust its observing schedule at all. For example, the 2015 Weather Forecasting System without the capability to perform targeted observing. The value of targeted observing could then be quantitatively assessed by comparing forecast track, storm intensity, and precipitation fields of both the control and the 2015 Weather Forecasting system with the nature run, which establishes "truth". It should be emphasized that the benefit of targeted observing would have to be proven over many such case studies.

VI.   Conclusions

Sensor Web observing systems may have the potential to significantly improve our ability to monitor, understand, and predict the evolution of rapidly evolving, transient, or variable environmental features and events. This improvement, however, will require considerable technology development and almost certainly involve a great amount of risk. A sensor web simulator is described that would allow science and engineering users to define, model, and objectively assess alternative sensor web system designs and to be able to quantitatively measure any improvement in predictive forecast skill. The potential payoff of introducing sensor web technology into an operational weather forecast system could thus be evaluated before large investments are made. A description of how the sensor web simulator could be used to model a future 2015 Weather Forecast System is also presented. As a representative example, we have described how the simulator could be applied to a real weather forecast scenario: the East Coast Blizzard of 2000.

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